

Effect of initial-state nucleon-nucleon correlations on collective flow in ultra-central heavy-ion collisions

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We investigate the effect of nucleon-nucleon correlations on the initial condition of ultra-central heavy ion collisions at LHC energies. We calculate the eccentricities of the MC-Glauber and IP-Glasma models in the 0–1% centrality class and show that they are considerably affected by the inclusion of such type of correlations. For an IP-Glasma initial condition, we further demonstrate that this effect survives the fluid-dynamical evolution of the system and can be observed in its final state azimuthal momentum anisotropy.

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INTRODUCTION

Various observations in ultra-relativistic heavy-ion collisions at the energies available at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) indicate that a quark-gluon-plasma (QGP) near thermodynamic equilibrium is created [1]. One of the most surprising results obtained at the RHIC, and later confirmed at the LHC, is that this novel state of nuclear matter behaves as an almost perfect fluid, with one of the smallest shear viscosity to entropy density ratios, η/s , ever observed in nature [2–6]. Currently, extracting the shear viscosity of the QGP from experiment is one of the main challenges in high energy nuclear physics.

The initial energy density profile of the QGP is one of the main ingredients in the fluid-dynamical simulation of a heavy ion collision. It is also one of the main sources of uncertainties when attempting to extract the properties of the QGP by fitting heavy ion collision measurements [7, 8]. There are several models used to provide this input, from the Monte-Carlo Glauber models [9] to saturation based models, such as the Monte-Carlo KLN [10], the rcBK [11, 12], or the IP-Glasma [13, 14] model. While these models differ in many aspects, they share one unique ingredient: they all require, as an input, the nucleon configurations of each colliding nucleus in an event. The fluctuation of such nucleon configurations on an event by event basis is a quantum effect and is the dominant contribution to the fluctuation of the azimuthal momentum distribution of charged hadrons observed at the RHIC and the LHC.

Practically all current initial condition models assume that the nucleons inside each colliding heavy ion are independent point-like particles, with positions prescribed according to a Woods-Saxon charge distribution function. This is, of course, a very crude approximation since it is well known that the nucleons inside nuclei are not independent from each other and should exhibit some degree of correlation. The question that follows is what kind of effect such nucleon-nucleon correlations can have

on the initial state of a heavy ion collision and whether the effect is strong enough to leave its imprints on the final state of the system.

In Ref. [15] Alvioli *et al* determined nucleon profiles of heavy nuclei that take into account the effect of nucleon-nucleon correlations. The phenomenological implications of such correlations on the initial state of heavy ion collisions were then investigated in Ref. [16]. Such studies were implemented for central and peripheral heavy ion collisions and indicated that the effect of correlations on the initial collision geometry was rather small. Additional studies on the effect of nucleon-nucleon correlations on the initial state of heavy ion collisions were also conducted in Refs. [17, 18] and similar conclusions were reached.

Recently, the CMS, ATLAS, and ALICE collaborations were able to isolate *ultra-central* heavy ion collisions [19–21] at the LHC, i.e., rare heavy ion collisions which have extremely large multiplicity and, consequently, a very large system size. By analyzing the collective flow signals of only such rare events, it is believed that an even more direct observation of the hydrodynamic behavior of QCD matter would be possible, allowing more accurate extractions of the viscous properties of the QGP [7]. However, one first has to determine whether a precise fluid-dynamical simulation of ultra-central collisions requires the inclusion of nucleon-nucleon correlations.

In this paper, we investigate for the first time the effect that nucleon-nucleon correlations can have on the initial condition of ultra-central heavy ion collisions at LHC energies. We show that the eccentricities of the MC-Glauber and IP-Glasma models in the 0–1% centrality class are considerably affected by the inclusion of such type of correlations. For an IP-Glasma initial condition, we further demonstrate that this effect survives the fluid-dynamical evolution of the system and can be observed in its final state azimuthal momentum anisotropy. The inclusion of correlations improves the agreement with experimental data noticeably, even though more work remains necessary in order to obtain a satisfactory agree-

ment.

EFFECT OF NUCLEON-NUCLEON CORRELATIONS ON ECCENTRICITIES

A key ingredient present in all initial state models is the configuration of the nucleons inside each nucleus participating in the collision. The position of the protons and neutrons inside the nucleus are usually sampled independently according to a Woods-Saxon distribution,

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)}. \quad (1)$$

For a Pb nucleus, the parameters R and a are given by $R = 6.62$ fm and $a = 0.546$ fm. The constant ρ_0 is the nucleon density and is not important when sampling the position of each nucleon since the distribution above is renormalized so that its integral in r becomes one. In this procedure all sources of nucleon-nucleon correlations are neglected.

Recently, Alvioli, Drescher and Strikman presented a Monte-Carlo generator of nucleon configurations that takes into account several sources of nucleon-nucleon correlations [15]. In their approach, the nucleus is described by a multiparticle wavefunction that depends on the position of all nucleons, as well as their spin and isospin. The position of each proton and neutron that constitutes the Pb nuclei is then found iteratively using the squared amplitude of the wave function [22] together with the constraint that, for every configuration, the single nucleon distribution function remains equal to the Woods-Saxon distribution shown above. Such configurations provide more realistic two-nucleon distribution functions than the ones obtained by sampling the nucleons independently, even if the excluded volume approximation is used in the latter procedure. In this work we study the effect of correlations by employing the Pb nuclei sampled by Alvioli *et al* using the formalism described in [15], which were made public and can be found in [23].

We note that, due to numerical limitations, the nuclei configurations presented in Ref. [15] did not take into account all the possible sources of correlations, i.e., only effective central correlations were introduced. Nevertheless, the aforementioned calculation should be able to capture the basic features of the 2-nucleon correlation functions and should provide a good insight when estimating the effect of correlations in ultra-central collisions. We note that more realistic configurations of nuclei were later calculated in Ref. [16], but only for Au nuclei and not for Pb.

In the Monte-Carlo Glauber model, the positions of the protons and neutrons of each heavy ion involved in the collision are used to calculate the position of the wounded nucleons and of binary collisions in the transverse plane of the reaction. The initial entropy density (or energy

density) of the system, s (or ε), is then assumed to scale as a linear combination of the density of binary collisions, n_{BC} , and the density of wounded nucleons, n_{WN} . That is, $s \sim f n_{BC} + (1-f) n_{WN}$, with f being the fraction of binary collisions. The main inputs required by the MC-Glauber model are the impact parameter of the collision, the corresponding nucleon-nucleon inelastic cross-section, σ_{NN} , and the probability distribution of a binary collision or wounded nucleon to create a certain amount of entropy, S . The overall normalization of the initial entropy density profile and the fraction of binary collisions are free parameters of the model, that should be determined so that the multiplicity distribution of the system is well reproduced. Here, we shall use $f = 0.14$, $\sigma_{NN} = 62$ mb, and an entropy distribution per binary collision/wounded nucleon given by a negative binomial distribution,

$$P(S) = \frac{\Gamma(S + \kappa)}{\Gamma(\kappa)\Gamma(S + 1)} \frac{r^S}{(r + 1)^{S+\kappa}}, \quad (2)$$

with $r = 18.4$ and $\kappa = 1.25$. These parameters provide a reasonable description of the multiplicity distribution of heavy ion collisions at the LHC.

On the other hand, in the IP-Glasma model the positions of protons and neutrons inside the nuclei are used to reconstruct the color charge density of the heavy ions colliding. This information is then used in the model to calculate the energy momentum tensor of the system at the initial stages of the collision, by solving the classical Yang-Mills equations. This model requires as an input the impact parameter of the collision and the thermalization time. The energy dependence of the local saturation scale, which affects the magnitude of the energy density, is given by the IP-Sat dipole model [24], with its parameters fit to deeply inelastic scattering data [25]. In the IP-Glasma model, negative binomial distributions appear naturally [26]. For details of this model, see Refs. [13, 14].

We first check the effect of correlations on the root mean square eccentricities $\varepsilon_n\{2\}$,

$$\varepsilon_n\{2\} \equiv \sqrt{\langle e_n e_n^* \rangle_{\text{events}}}, \quad e_n = \langle r^n \exp(in\phi) \rangle_{\varepsilon,s}, \quad (3)$$

of the initial state profile of the MC-Glauber and IP-Glasma models. Above, the brackets denote the spatial integrals (performed in a given event), $\langle \dots \rangle_A = \int r dr d\phi (\dots) A(r, \phi, \tau_0)$, with r and ϕ being the coordinates in the transverse plane, τ_0 the thermalization time, and A is either the entropy density, s , or the energy density, ε . The eccentricities characterize the transverse shape of the fluid at the thermalization time τ_0 and influence directly the magnitude of the anisotropic flow produced during the fluid-dynamical evolution of the system [27, 28].

In Fig. 1 we show the root mean square eccentricities $\varepsilon_n\{2\}$, for $n = 2-6$, for Pb-Pb collisions in the 0-1% centrality class. We note that the bracket $\langle \dots \rangle_{\text{events}}$ denotes an average over events. We present results for

the MC-Glauber model (top panel) and the IP-Glasma model (bottom panel). In this work, the eccentricities of the Glauber model were computed using the entropy density as weights while those of the IP-Glasma model were computed using energy density as weights. The blue lines correspond to the results with nucleon-nucleon correlations while the red lines to the results without such correlations. The effect of correlations is the largest for IP-Glasma initial conditions, where ε_2 changes by almost 20% with the inclusion of nucleon-nucleon correlations. For the MC-Glauber model considered the effect of correlations on the eccentricities becomes smaller, with ε_2 being reduced by 10% with the inclusion of correlations. We note that the effect of nucleon-nucleon correlations on the MC-Glauber model depends on the fraction of binary collisions. If we had taken $f = 1$, the changes in eccentricity would become considerably larger, even though not as large as those occurring for IP-Glasma initial conditions. However, when $f = 1$ one cannot describe the multiplicity distribution of heavy ion collisions very well, so we refrain from including such results in this paper.

We checked that, for non-central collisions in the 20-30% centrality class, the effect of correlations on the eccentricities become very small for both initial condition models.

In the following, we shall demonstrate that such changes in the eccentricities of the IP-Glasma initial condition can lead to large changes on the transverse momentum anisotropy of the final state of the collision.

FLUID-DYNAMICAL SIMULATION OF ULTRA-CENTRAL COLLISION

In order to calculate the flow harmonics, one must compute the fluid-dynamical evolution of the bulk nuclear matter created in the collision. In the following study the initial state is given by the IP-Glasma model, in the 0-1% and 2.5-5% centrality classes, with a thermalization time of $\tau_0 = 0.4$ fm. The fluid-dynamical evolution of the system with this initial state is solved numerically using the MUSIC simulation [29, 30]. The main equations of motion solved by MUSIC are the conservation laws of energy and momentum,

$$\partial_\mu T^{\mu\nu} = 0, \quad (4)$$

where $T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - g^{\mu\nu}P + \pi^{\mu\nu}$, with ε , P , u^μ , and $\pi^{\mu\nu}$ being the energy density, thermodynamic pressure, 4-velocity, and shear-stress tensor, respectively. The time evolution of $\pi^{\mu\nu}$ is obtained by solving a version of Israel-Stewart theory [32, 33],

$$\tau_\pi \dot{\pi}^{(\mu\nu)} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \frac{4}{3}\tau_\pi\pi^{\mu\nu}\partial_\mu u^\mu, \quad (5)$$

where $\dot{\pi}^{(\mu\nu)} \equiv \Delta_\alpha^\mu \Delta_\beta^\nu u^\lambda \partial_\lambda \pi^{\alpha\beta}$, with $\Delta_\alpha^\mu = g_\alpha^\mu - u^\mu u_\alpha$ being the projection operator orthogonal to the flow ve-

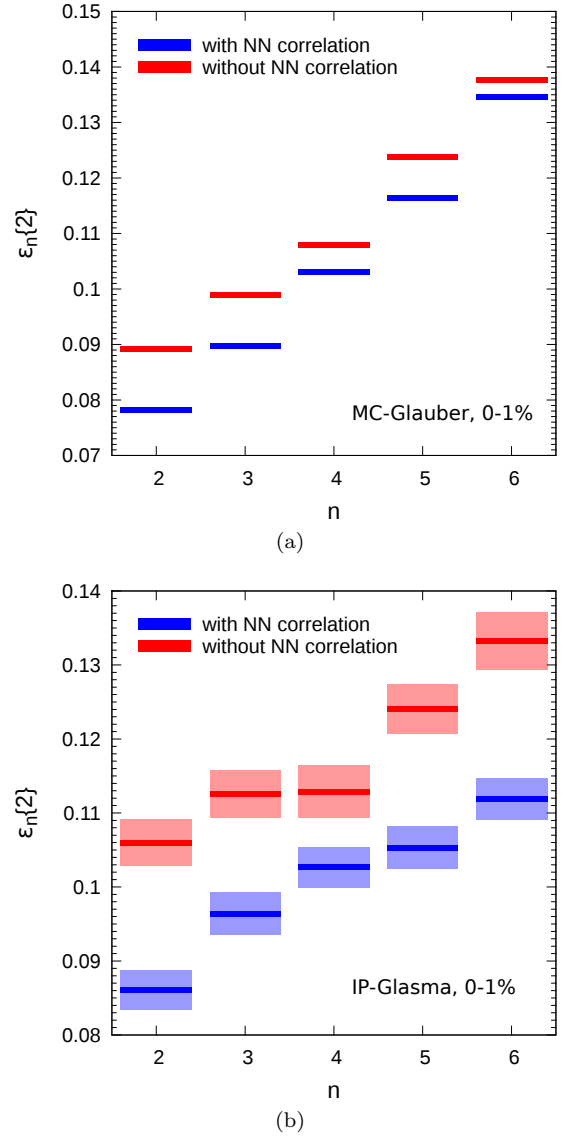


FIG. 1: (Color online) Comparison of the eccentricities, $\varepsilon_n\{2\}$, of the MC-Glauber model (top panel) and IP-Glasma model (bottom panel) with (blue) and without (red) the effect of nucleon-nucleon correlations. The results shown are for the 0-1% most central events. The statistical uncertainty of the calculation is given by the bands.

locity. In our calculations the flow velocity is defined according to the Landau picture [34], i.e., $T^{\mu\nu}u_\mu = \varepsilon u^\nu$. The equation of state, $P(\varepsilon)$, employed in our simulation is the s95p-PCE-v1 parametrization of lattice QCD calculations [35], with a chemical freeze-out temperature of $T_{\text{chem}} = 150$ MeV. The shear viscosity to entropy density ratio is set to $\eta/s = 0.22$ and the relaxation time is given by $\tau_\pi = 5\eta/(\varepsilon + P)$. Finally, we used a freeze-out temperature of $T = 103$ MeV. We note that these parameters are not exactly the same as those employed in Ref. [31]. Nevertheless, we checked that they are able to provide an equally good description of semi-peripheral

and peripheral heavy ion collisions at LHC energies [36]. We note that the value of η/s employed in our calculation is slightly higher than the one used in Ref. [31], but this is mainly due to the difference in the freezeout temperatures employed in each calculations.

We compute the root mean square of the flow harmonic coefficients, V_n ,

$$v_n\{2\} = \sqrt{\langle V_n V_n^* \rangle_{\text{events}}}, \quad V_n = \langle \exp(in\phi) \rangle, \quad (6)$$

where ϕ is the azimuthal transverse momentum angle and the bracket denotes the following averaging procedure (performed in a given event)

$$\langle \cdots \rangle = \frac{\int d\phi d^2p_T f(p_T, \phi) \times (\cdots)}{\int d\phi d^2p_T f(p_T, \phi)}, \quad (7)$$

with f_p being the single particle probability distribution function obtained from the Cooper-Frye formalism [37]. As before, the bracket $\langle \cdots \rangle_{\text{events}}$ denotes an average over events. The nonequilibrium momentum distribution function of hadrons, $f^i(k)$, included in the Cooper-Frye description is given by the usual 14-moment approximation [32],

$$f^i(k) = f_0^i(k) \left[1 + \tilde{f}_0^i(k) \frac{\pi^{\mu\nu} k_i^\mu k_i^\nu}{2(\varepsilon + P)T^2} \right],$$

where the index i refers to the corresponding hadron species, k_i^μ is the 4-momentum of the i -th species, $f_0^i(k)$ is the Bose-Einstein/Fermi-Dirac distribution, and $\tilde{f}_0^i(k) = 1 - a f_0^i(k)$, with $a = 1(-1)$ for fermions(bosons). The energy density, pressure, temperature, and shear-stress tensor in this expression are those in the freeze-out surface elements, that we sum over to get the particle spectra. In this calculation, we include all hadrons/resonances with masses up to 1.3 GeV and consider all 2-body and three-body decays of unstable resonances.

The flow harmonics calculated with and without the effect of correlations are compared to CMS data [19] in Fig.2(a) for the 0–1% centrality class. In order to compare with CMS measurements, we introduced a lower cut-off of 0.3 GeV on the transverse momentum integrals. We see a very large effect of nucleon-nucleon correlations on the elliptic and triangular flow of ultra-central collisions. As expected, the effect is rather similar to the one encountered for the initial state eccentricities. We note that the introduction of correlations produces a large reduction of the elliptic flow coefficient, leading to a better agreement with the CMS data.

For the sake of completeness, we also check the effect of correlations in the 2.5–5% centrality class, which would be usually referred to as central collisions. In Fig.2(b), we compare flow harmonics calculated with and without the effect of correlations to CMS data in this centrality class. We still observe some effect of correlations on the

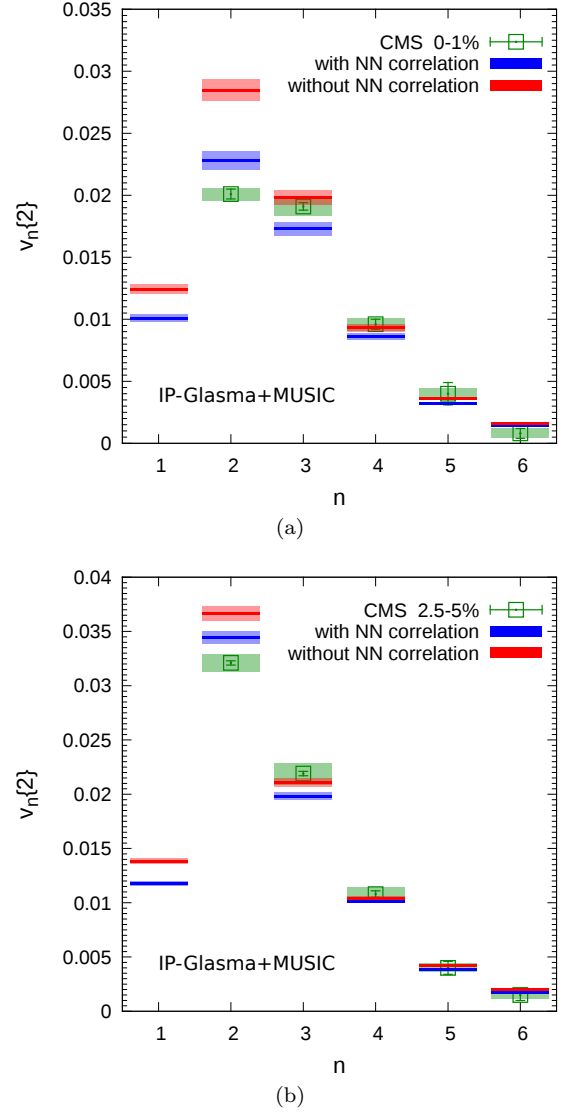


FIG. 2: (Color online) Comparison of the flow harmonics, $v_n\{2\}$, calculated using IP-Glasma initial conditions with (blue bars) and without (red bars) the effect of correlations, with CMS data (green squares) for the 0–1 % (top panel) and 2.5–5 % (bottom panel) centrality classes. The statistical uncertainty of the calculation is given by the bands. For the experimental points, the bands denote systematic uncertainties while the bars denote the statistical uncertainty.

elliptic and triangular flow of the system. Nevertheless, the effect is considerably smaller than the one observed in the ultra-central collisions.

We remark that the agreement between theory and experiment is still not satisfactory in ultra-central collisions. While inclusion of nucleon-nucleon correlations did improve the overall agreement between the flow harmonics measured by CMS and those calculated from fluid-dynamical simulations, the values of elliptic flow and triangular predicted from theory are still not in agreement with the values observed by the experiments: The el-

liptic flow coefficient calculated with the fluid-dynamical simulation is above the data while the triangular flow coefficient is slightly below the data. The same would be true if we had compared to data from the ATLAS or ALICE experiments, which differ from CMS data by having different transverse momentum cuts.

Such partial disagreement with the data can happen because the effects of nucleon-nucleon correlations were only partially included, e.g., the effect of short-range attractive interactions and of 3-nucleon correlations were not taken into account. Previous results indicate that the inclusion of attractive interactions may reduce the effect of central correlations on the initial state eccentricities. On the other hand, this has never been checked for IP-Glasma initial conditions and will be an interesting project for the future. It is also possible that such disagreement with the data may originate from the fluid-dynamical simulation of the bulk QCD matter itself. Our calculation did not take into account some sources of dissipation such as bulk viscosity and also did not include higher-order non-linear terms that appear in the fluid-dynamical equations of motion [38]. We shall discuss these two ingredients in future publications.

CONCLUSIONS

In this paper, we calculated the effect of nucleon-nucleon correlations on the initial state of ultra-central heavy ion collisions. We showed that these correlations have a large effect on the eccentricities of the MC-Glauber and IP-Glasma models, leading to significant reduction of ε_2 and ε_3 . For IP-Glasma initial conditions, we further calculated the final state momentum anisotropy coefficients, $v_n\{2\}$, and demonstrated that they are also considerably affected by the initial state nucleon-nucleon correlations. Overall, the inclusion of nucleon-nucleon correlations improves the agreement with experimental measurements of flow coefficients and is a first step towards achieving a reasonable description of such rare events. This indicates that ultra-central collisions might be ideal, not only to investigate the bulk properties of hot and dense nuclear matter, but also to study correlations of the initial state wave function, thus providing a fascinating connection between the physics of relativistic heavy-ion collisions and that of nuclear structure.

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- [1] See, for instance, C. Gale, S. Jeon and B. Schenke, *Int. J. Mod. Phys. A* **28**, 1340011 (2013), and references therein.
 - [2] BRAHMS collaboration, *Nuclear Physics A* **757** 1, 1 (2005).
 - [3] PHENIX collaboration, *Nuclear Physics A* **757** 1, 184 (2005).
 - [4] PHOBOS collaboration, *Nuclear Physics A* **757** 1, 28 (2005).
 - [5] STAR collaboration, *Nuclear Physics A* **757** 1, 102 (2005).
 - [6] See, for instance, Y. Schutz and U. Wiedemann, *J. Phys. G: Nucl. Part. Phys.* **38**, 120301 (2011), and all papers in this volume.
 - [7] M. Luzum and J. -Y. Ollitrault, *Nucl. Phys. A* **904-905**, 377c (2013).
 - [8] H. Song and U. W. Heinz, *J. Phys. G* **36**, 064033 (2009) [arXiv:0812.4274 [nucl-th]].
 - [9] M. L. Miller, K. Reygers, S. J. Sanders and P. Steinberg, *Ann. Rev. Nucl. Part. Sci.* **57**, 205 (2007) [nucl-ex/0701025].
 - [10] D. Kharzeev, E. Levin and M. Nardi, *Phys. Rev. C* **71**, 054903 (2005); D. Kharzeev, E. Levin and M. Nardi, *Nucl. Phys. A* **747**, 609 (2005).
 - [11] J. L. Albacete, A. Dumitru, H. Fujii and Y. Nara, *Nucl. Phys. A* **897**, 1 (2013).
 - [12] A. Dumitru and Y. Nara, *Phys. Rev. C* **85**, 034907 (2012).
 - [13] B. Schenke, P. Tribedy and R. Venugopalan, *Phys. Rev. Lett.* **108**, 252301 (2012) [arXiv:1202.6646 [nucl-th]].
 - [14] B. Schenke, P. Tribedy and R. Venugopalan, *Phys. Rev. C* **86**, 034908 (2012) [arXiv:1206.6805 [hep-ph]].
 - [15] M. Alvioli, H. -J. Drescher and M. Strikman, *Phys. Lett. B* **680**, 225 (2009) [arXiv:0905.2670 [nucl-th]].
 - [16] M. Alvioli, H. Holopainen, K. J. Eskola and M. Strikman, *Phys. Rev. C* **85**, 034902 (2012) [arXiv:1112.5306 [hep-ph]].
 - [17] J. -P. Blaizot, W. Broniowski and J. -Y. Ollitrault, arXiv:1405.3274 [nucl-th].
 - [18] W. Broniowski and M. Rybczynski, *Phys. Rev. C* **81**, 064909 (2010).
 - [19] S. Chatrchyan *et al.* [CMS Collaboration], *JHEP* **1402**, 088 (2014) [arXiv:1312.1845 [nucl-ex]].
 - [20] G. Aad *et al.* [ATLAS Collaboration], *Phys. Rev. C* **86**, 014907 (2012) [arXiv:1203.3087 [hep-ex]].
 - [21] K. Aamodt *et al.* [ALICE Collaboration], *Phys. Rev. Lett.* **107**, 032301 (2011).
 - [22] M. Alvioli, C. Ciofi degli Atti and H. Morita, *Phys. Rev. C* **72**, 054310 (2005) [nucl-th/0506054].
 - [23] The Pb nucleon configurations computed by Alvioli *et al.* can be found on the website <http://users.phys.psu.edu/~malvioli/eventgenerator/>.
 - [24] H. Kowalski and D. Teaney, *Phys. Rev. D* **68**, 114005 (2003) [hep-ph/0304189].
 - [25] A. H. Rezaeian, M. Siddikov, M. Van de Klundert and

- R. Venugopalan, Phys. Rev. D **87**, no. 3, 034002 (2013) [arXiv:1212.2974].
- [26] B. Schenke, P. Tribedy and R. Venugopalan, Phys. Rev. C **89**, 024901 (2014) [arXiv:1311.3636 [hep-ph]].
- [27] D. Teaney and L. Yan, Phys. Rev. C **86**, 044908 (2012).
- [28] H. Niemi, G. S. Denicol, H. Holopainen and P. Huovinen, Phys. Rev. C **87**, 054901 (2013).
- [29] B. Schenke, S. Jeon and C. Gale, Phys. Rev. C **82**, 014903 (2010) [arXiv:1004.1408 [hep-ph]].
- [30] H. Marrochio, J. Noronha, G. S. Denicol, M. Luzum, S. Jeon and C. Gale, arXiv:1307.6130 [nucl-th].
- [31] C. Gale, S. Jeon, B. Schenke, P. Tribedy and R. Venugopalan, Phys. Rev. Lett. **110**, 012302 (2013).
- [32] W. Israel and J. M. Stewart, Ann. Phys. (N.Y.) **118**, 341 (1979).
- [33] G. S. Denicol, H. Niemi, E. Molnar and D. H. Rischke, Phys. Rev. D **85**, 114047 (2012).
- [34] L.D. Landau and E.M. Lifshitz, *Fluid Mechanics*, (Pergamon; Addison-Wesley, London, U.K.; Reading, U.S.A., 1959).
- [35] P. Huovinen and P. Petreczky, Nucl. Phys. A **837**, 26 (2010).
- [36] Such fits to data were presented in the poster section by J.-F. Paquet *et al* in the Quark Matter 2014 conference.
- [37] F. Cooper and G. Frye, Phys. Rev. D **10**, 186 (1974).
- [38] G. S. Denicol, S. Jeon and C. Gale, arXiv:1403.0962 [nucl-th].